

****FULL TITLE****

*ASP Conference Series, Vol. **VOLUME**, **YEAR OF PUBLICATION***

****NAMES OF EDITORS****

Invisible Plasma Content in Blazars? The Case of Markarian 421

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Abstract.

Invisible plasma content in blazar jets such as protons and/or thermal electron-positron (e^\pm) pairs is explored through combined arguments of dynamical and radiative processes. By comparing physical quantities required by the internal shock model with those obtained through the observed radio-to-gamma-ray spectra for Mrk 421, we find the existence of a copious amount of invisible plasma in the jet. We speculate that the blazar sequence could arise from variations of total amount and/or blending ratio of e^\pm pair and electron-proton plasma.

1. Introduction

The plasma content of relativistic jets is not easily constrained by observations since the emission is dominated by that from non-thermal electrons and it is difficult to directly constrain thermal plasma. Hence, the plasma composition in AGN jets, whether normal proton-electron (e/p) plasma or electron-positron pairs (e^\pm) is a dominant composition, is still a matter of debate (e.g., Reynolds et al. 1996; Wardle et al. 1998; Hirotani et al. 1999; Sikora & Madejski 2000). This problem prevents us from estimating the total mass and energy flux ejected from a central engine. In order to constrain the invisible matter in the jets, dynamical considerations are indispensable. In Kino & Takahara (2004), we proposed a new procedure to constrain the invisible plasma component in classical FR II radio sources. We used the fact that the mass and energy densities of the sum of thermal and non-thermal (NT hereafter) particles are larger than those of non-thermal electrons which are determined by observations. We apply the same technique to the inner core jets of AGNs (i.e., blazars) based on the standard internal shock model (Kino & Takahara 2008).

2. Mass density of invisible plasma

The methodology of constraining the invisible plasma content in the emission region is as follows. A lower limit to the total mass density (sum of non-thermal electrons and invisible plasma) is restricted by the definition that the mass

density of total plasma (ρ) should be smaller than that of the non-thermal electrons (ρ_e^{NT}). Similarly, a lower limit to the total internal energy density (e) is limited by the definition that e is smaller than that of the NT electrons (e_e^{NT}). Using a relativistic shock jump conditions, we can estimate the values of ρ and e (see Kino & Takahara 2008). The mass density of non-thermal electrons of TeV blazars can be well estimated by the fitting of a multi-frequency spectrum with synchrotron self-Compton (SSC) model (Kino et al. 2002, hereafter KTK). The number density of non-thermal electrons n_e^{NT} has been estimated as $n_e^{\text{NT}} \equiv \int_{\gamma_{e,\min}}^{\infty} n_e(\gamma_e) d\gamma_e$, while e_e^{NT} is given by $e_e^{\text{NT}} = \langle \gamma_e \rangle n_e^{\text{NT}} m_e c^2$, where $n_e(\gamma_e)$ and $\langle \gamma_e \rangle$ are the energy spectrum and the average Lorentz factor of NT electrons, respectively. By a detailed comparison of the SSC model with the observed broadband spectrum of Mrk 421, we obtained n_e^{NT} as $n_e^{\text{NT}} \simeq 11 \times (\gamma_{e,\min}/10)^{-0.6} \text{ cm}^{-3}$. Here we adopt the index of injected electrons for Mrk 421 as $s = 1.6$ (e.g., Kirk & Duffy 1999). As for the average energy of NT electrons, we obtained

$$e_e^{\text{NT}}/n_e^{\text{NT}} = \langle \gamma_e \rangle m_e c^2 \simeq 3.1 \times 10^2 m_e c^2, \quad (1)$$

where $\langle \gamma_e \rangle$ is the average Lorentz factor of NT electrons. Since for $s = 1.6$, electrons near the cooling break energy $\gamma_{e,\text{br}} \approx 10^4$ carry most part of the kinetic energy and e_e^{NT} has a weak dependence on the minimum Lorentz factor $\gamma_{e,\min}$. In Fig. 1, we show that the case of $\gamma_{e,\min} \approx 10^4$ is ruled out for Mrk 421 since the case does not fit the EGRET data (KTK). Therefore, Eq. (1) is justified in any case for Mrk 421.

The condition of $e_e^{\text{NT}}/e = \langle \gamma_e \rangle \rho_e^{\text{NT}}/\Gamma_{\text{rel}}\rho < 1$ can be rewritten as

$$\frac{\rho}{\rho_e^{\text{NT}}} > \frac{\langle \gamma_e \rangle}{\Gamma_{\text{rel}}} \simeq \frac{3.1 \times 10^2}{\Gamma_{\text{rel}}}, \quad (2)$$

where Γ_{rel} is the relative bulk Lorentz factor between an upstream and a downstream of the shock. From this, we directly see that the invisible mass density at least about 100 times the rest mass density of NT electrons is definitely required in the framework of internal shock model in which $\Gamma_{\text{rel}} \leq \text{a few}$ takes place. In other words, a loading of baryons and/or a thermal pair plasma is expected. As for the upper limit, we use the constraint that bremsstrahlung emission from thermal electron (and positron) component should not exceed the observed γ -ray emission. We can thus bracket the amount of total mass density in the emission region from below and above. In this way we apply this method to the TeV blazar Mrk 421.

In Fig. 2 we show the resultant ρ/ρ_e^{NT} plotted versus Γ_r/Γ_s in the cases of “equal ρ ” and “equal mass” ($m = \rho\Gamma\Delta$) where Γ_r , Γ_s , and Δ denote the Lorentz factors of rapid and slow shell, and the thickness of the shell measured in ISM frame, respectively. We impose the condition $\Delta_r/\Delta_s = 1$ (e.g., Spada et al. 2001). As for the plasma content, we examined the two simple cases. One is the case of the jet with pure e^\pm pair plasma content, whilst the other is the jet made of pure e/p plasma. The qualitative features are the same for these two cases, although different in quantitative detail. Central to the results is that a large amount of mass density of invisible plasma is clearly required in the emission region. As the value of Γ_r/Γ_s increases, the value of Γ_{rel} becomes larger and the lower limit on the invisible mass density (ρ/ρ_e^{NT}) reduces.

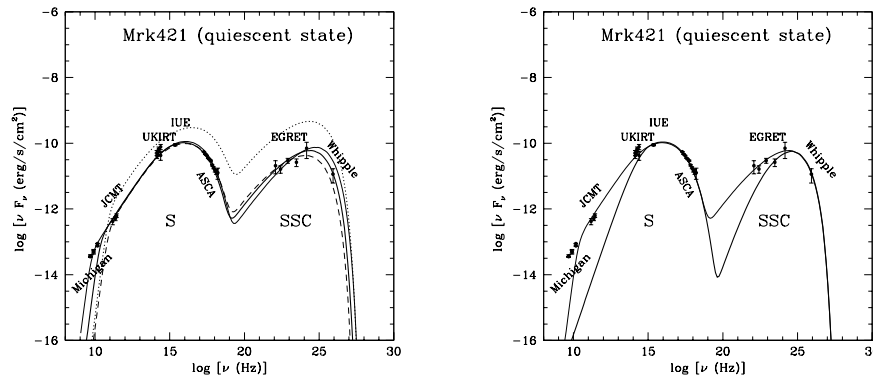


Figure 1. One-zone SSC model spectra for the steady state emission of Mrk 421 (KTK). The thick solid line in the left one shows the best fit spectrum. In the right one, we examine the case of $\gamma_{e,\min} = 10^4$ (the thick solid line). The case of $\gamma_{e,\min} = 10^4$ is ruled out because it cannot fit the spectrum well.

3. Discussion

Let us discuss the origin of blazar sequence (Fossati et al. 1998) which is tightly connected to the nature of the central engine. In Fossati et al. (1998) they computed average spectral energy distributions from radio to gamma-rays for complete sample of blazars. They claimed that the continuous sequence of properties may be controlled by a single parameter, related to the bolometric luminosity. Here we enlighten another new ingredient for the origin of sequence. Flat spectrum radio quasars (FSRQs) have the order of magnitude larger kinetic power and larger energy density of the surrounding external radiation field than BL Lacs (e.g., Sikora et al. 1997). Hence the leptonic components in FSRQs ejecta undergo severe radiation drag in dense external radiation fields (Sikora & Wilson 1981; Phinney 1982). However, the bulk Lorentz factors in FSRQs are slightly larger than the ones in TeV blazars (Jorstad et al. 2001; Kellermann et al. 2004) in spite of being subject to much stronger radiation drag (e.g., Kubo et al. 1998; Spada et al. 2001). In order to realize the larger kinetic powers and larger bulk Lorentz factors against the strong radiation drag, we may take a new conjecture that a larger baryon loading may occur for FSRQs. Summing up, not only the strength of the external radiation field but also the total amount and/or blending ratio of e^\pm pair and e/p could be new key quantities to explore the origin of the continuous blazar sequence.

Acknowledgments. We acknowledge the Grant-in-Aid for Scientific Research of the Japanese Ministry of Education, Culture, Sports, Science and Technology, No. 14079025, 14340066, and 16540215.

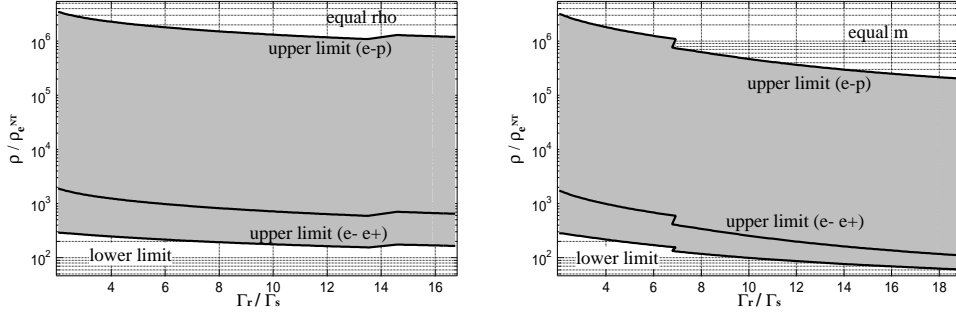


Figure 2. The allowed regions (the gray shaded regions) of ρ/ρ_e^{NT} ; the amount of mass density of total plasma normalized by that of non-thermal electrons for “equal ρ ” (left) and “equal m ” (right). Horizontal axis shows the ratio of the Lorentz factor of a rapid shell to a slow one.

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